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Comments on the proposed ruling to permit use of the US Navy's "Surveillance Towed Array Sensor System Low Frequency Active Sonar" (LFA).

Dear Ms. Wieting:

Thank you for the opportunity to comment on NMFS' proposed rulemaking for the Navy's SURTASS LFA system. My qualifications include a Ph.D. in oceanography and some 20 years' experience working in oceanography and acoustics, more recently including marine mammal acoustics

It is my understanding that, under the 'U.S. Marine Mammal Protection Act, NMFS has a fundamental obligation to ensure that LFA has a "negligible impact" on marine mammals before it may grant the Navy a permit. I have been following the issues surrounding the development and proposed deployment of the US Navy's Low Frequency Active Sonar (LFA) with considerable concern. I have contributed to the LFA EIS through submitted comments on the draft of that document, and have read the Navy's response. I continue to find it scientifically seriously flawed. I am concerned, therefore, that the rule NMFS has proposed relies on the analysis presented by the Navy in its environmental review. In several crucial respects, a few of which I discuss below, NMFS underestimates or fails to address LFA's potential for harm, and does not reflect the best available science. All my original concerns, as voiced in previous comments to the Navy in October 1999, remain and should be taken with this document as current and as an implicit inclusion. In addition, I would like to add the following new areas of comments.

Use of far-field versus near-field source level values

When there is a need to produce a sound of great amplitude, it simply cannot be done by a physically smail aperture, since it would cavitate in the negative pressure phase of the oscillation. Actually, all sources have finite size, and the near-field/far-field issue occurs for all sources at sufficiently small range. The question is, at what range do we need to consider near-field complications, and beyond what range can we consider we are in the far-field? This depends on the source size itself. If the source consists of an array of individual sources, we need to consider not the physical size of each component, but the array aperture to determine where the near-field becomes indistinguishable from a far-field approximation. The far-field approximation assumes that, for all intent and purposes, the sound emanates from a point source of given strength referenced to a standard distance (normally 1 metre). This approximation is therefore appropriate at sufficiently large range where the detailed structure of individual source elements cannot be determined, i.e. the structure of the actual source array has no impact on the field at ranges larger or equal to the range being considered.

Near enough to any source, the field becomes more complicated as the distance to various parts of the source structure differ significantly, resulting in phase and amplitude changes in the contributions from those parts.

Far enough from a source, the entire source aperture appears point-like, and the field becomes simpler. In an unbounded homogeneous isotropic medium, we see a spherically symmetric field.

For argument's sake, suppose the LFA source array far-field strength (referenced to lm) is 240 dB re 1 microPascal. The leading marine mammal hearing experts (such as Ridgway, Ketten, Schuster-man, Bowles, Tyack and Thomas) agree that 180 dB is a conservative level for cetaceans for an impulsive sound. Longer-duration sounds (several seconds) should therefore be assigned a lower limit, perhaps in the region of 170 dB. The LFA transmissions are certainly long enough (about 60 seconds) to qualify for the lower limit. Even if we are interested in the higher level of 180 dB, an approximate estimate indicates that with (the most favourable) spherical spreading we can expect this to occur at around 1 km from the LFA. If this range is much greater than the source aperture (the case for LFA) then we are justified in using the far-field approximation. This allows us to ignore the detailed internal structure of the source array and use only the far-field point-like approximation, in which case the source array can be completely characterised by a single number, a source strength that we normalise (for convenience's sake) to lm.

If we were interested in higher dB values, then we would have to accept that the point-source approximation applicable to the far-field would no longer be appropriate, and one would have to deal with the spatially-complicated structure of the field in the near-field range. One of the consequences of this would be that we would never actually find a source level anywhere near as high as the point-like far-field value of 240 dB re 1 microPascal @ lm, because we could never actually get within lm of all the source elements in the array. It is my understanding that, for LFA, the transition between a valid far-field approximation to near-field occurs at some 200 m range, and therefore at levels considerably above 180 dB re 1 microPascal.

For marine mammals, by the time we have reached 180 dB re 1 microPascal we are at a level where experts agree there is substantial risk of physiological trauma, and higher levels become academic for the purposes of considering the avoidance of damaging impact, even if psychological impact is considered'acceptable (a view I do not share).

We can therefore safely use the far-field approximation for considering LFA impact on marine mammals, and this is the appropriate approach, because at 1 km the source behaves as if it did indeed come from a point-like region of that strength. It is therefore misleading and inappropriate to quote individual source levels in LFA marine mammal evaluation discussions.

If you modelled the full structure of the array and integrated with the appropriate phase over all elements (the approach required in the near field) at 1 km or more you'd just get the same answer in the far field as assuming the energy came from a point-like source. In other words, given any receiving instrument (including a mammal ear) placed at 1 km or more (actually more like 200 m) from the LFA array, the acoustic field will behave and be measured exactly as if it came from a single source of strength SLA = SLS + 20 log(N) - SLL, where SLS is the actual source level of a single source, N is the number of identical sources in the array and SLL is an inefficiency loss due to imperfectly coherent excitation. There is absolutely no doubt that at ranges of 1 km and over the LFA array is not fairly characterised by the SLS value and must logically be considered as if it were a single point source for considerations of received source level.

On appropriate *models* for evaluating *potentially* damaging *exposure*

I believe it makes sense to consider guidelines for exposure levels as an integrated exposure at levels that are thought to induce temporary threshold shift (TT'S) with an absolute never-exceed' limit at the point thought to induce permanent threshold shift (PTS) or other damage.

Regarding the never-exceed level, once a marine mammal has been exposed to 180 dB or more, it has very likely sustained physiological trauma and, in my opinion, has therefore already been exposed to unacceptable levels of man-made sound. There is no doubt in my mind that 180 dB is at or above the maximum 'never exceed' level appropriate for the health of marine mammals and this is consistent with all the published scientific evidence that I am aware of.

Regarding the integrated exposure part of the issue, this is based on the idea of avoiding accumulated TTS. Kastak and Schusterman have shown that TTS occurs 145 dB for 20 - 25 min in pinnipeds. Cetaceans generally have more sensitive hearing (since they are optimised for water, whereas Pinnipeds are optimised for air and water), by about 10 dB, so we can expect TTS to occur in some species at about 135 dB for the same exposure time. The LFA signal lasts about 1 minute. If we model TTS as accruing linearly with time (perhaps the best and simplest model consistent with the limited data available), we can therefore expect TTS in some species at levels of 135 + (26-28) dB (allowing for the decrease in time from 20-25 to 1 minute). Available evidence therefore suggests TTS probably starts for most marine mammals whose hearing is in the source range at about 162 dB for a single LFA transmission exposure, with PTS occurring in the region of 180 dB, if not more damaging trauma leading almost directly to death via beaching, etc. If an animal is exposed to more than one LFA transmission sequence, the level at which TTS would occur would obviously be lowered.

My personal speculation is that marine mammal ears appear to be able to adapt evolutionarily to sensitivities around 60 dB re 1 microPascal in water if this is advantageous in an evolutionary sense. Using a 26 dB correction factor for referencing to 20 microPascals and a further 36 dB for the difference in density and sound speed between air and water gives about 0 dB re 20 microPascals in air which is about right for terrestrial mammals, supporting this general estimate for evolutionarily-optimised sensitivity.

Mammalian ears also seem to have about 100 dB of dynamic range, probably a fairly robust feature of the basic physiological design. Above this, TTS occurs.

If we take permanent, irreversible damage to be the limiting criteria for LFAS permissible operation (a criteria I find too generous to LFAS) then I would therefore expect 160 dB to be about the right figure to induce TTS for prolonged sounds, based on phenomenological evidence about the class of mammalian ears in general.

The fact that two quite independent (though each speculative in different ways) trains of argument lead to broadly the same figure lends confidence that 160 dB is probably a good value to use for marine mammal TTS for a 60-second exposure.

Possible resonant damage

In addition to potential damage to hearing mechanisms, there is another issue of possible lung resonance damage. As a crude model to investigate this mechanism to see if it is plausible, one may consider the lungs either as an air bubble or bubbly mixture.

Neglecting surface tension and other dissipation mechanisms, and assuming no heat migrates across the bubble wall as it expands and contracts (known to be a good approximation for 'freely-oscillating' bubbles) the resonant frequency of a spherical cavity is given by Minneart's frequency:

f = (1/(2*pi*R)) * sqrt((3*gamma*p)/rho)

if we include a viscous wall we get a modified formula:

f = (1/(2*pi*R)) * sqrt((3*gamma*p + 4*u)/rho), where:

R = radius [m] of the bubble. If this is a sealed bubble (like a lung in a diving mammal), we can calculate the approximate volume and hence radius, which will reduce as the depth increases according to Boyle's law. The volume at depth d is V = VO / (1 + d * 0.0993939) where VO is the volume at the surface and V = (4*pi*R^3)/3.

gamma = is the ratio of specific heats (1.4 for air).

p = pressure [N/m^2] = atm * 10^5, where atm = 1 + d * 0.0993939

d is the depth [m].

u = shear modulus of whale flesh (about 10^5 [N/m^2] which is actually the approximate shear modulus for fish flesh, but I have no better information)

rho = the density of seawater = 1025 [kg/m^3].

So, the resonant bubble frequency depends on pressure and radius.

A paper by E.G. Barham ("Whales' Respiratory Volume as a Possible Resonant Receiver for 20 Hz Signals", Nature, Vol. 245, September 28 1973, pg 220) treats whale lungs as a pure bubble, less accurate than considering it a mix of bubbles and tissue, but it does include tissue shear effects.

Some resonant frequencies from E.G. Barham's paper for a bubble of 2000 litres at the surface, taken to various depths are:

depth d [m]	bubble radius R [m]	frequency f [Hz]
0	0.782	5.8
15	0.577	10.4
30	0.493	14.5
40	0.458	17.1
50	0.43 1	19.7
60	0.409	22.1
100	0.352	31.6
200	0.284	53.0

Based on this model, we can calculate a rough example table of the bubble size required to match resonance frequencies of 100 and 500 Hz (d100Hz and d500Hz respectively) at various depths (not including tissue strength, for a spherical bubble)

Depth [m]	d100Hz [m]	d500Hz [m]
0	0.032	0.006
10	0.046	0.009
20	0.056	0.011
50	0.079	0.016
100	0.108	0.022
200	0.149	0.030
500	0.23 1	0.046

For a lung volume of about 4 litres (approximately representative of a human or small porpoise, perhaps), a spherical bubble of equivalent volume would have a radius of about 0.01 m. This would resonate at about 320 Hz at the surface, and 500 Hz at 20 m depth.

Resonances occur in all structures, spherical or not. Non-spherical shapes are just less simple to calculate.

There are also many papers and publications treating fish swim bladders as resonant bubbles that might be used to estimate this kind of resonance.

If the cavity is surrounded by tissue that can support shear forces, the issue becomes much more complicated. The surrounding tissue will modify the resonant frequency and provide dissipative mechanisms via shear-wave conversion, viscosity and heat conduction.

For lung tissues, there are many very small cavities distributed through an almost homogeneous medium, and this may well be better modelled as a collective bubble mass, which is known to have different properties. Collective bubbles can resonate at much lower frequencies than individual bubbles within the mass, there is a resonant collective oscillation that corresponds to the oscillation of the entire mass with the mean density associated with the tissue-bubble mixture.

To get resonance at a few hundred Hz you need large bubbles. In mammals, the issue is probably lung tissue, which needs to be treated as a shaped collective bubble medium with shear properties to be reasonably accurate.

The, acceleration of the cavity walls will cause shear forces in tissues that support it. Water does not support shear forces and can act as a lubricant to fill spaces and move around to reduce pressure gradients in more rigid tissue matrices.

If the sound is a linear propagating wave (good for LFA levels) then the principle of superposition applies and the response at each frequency is uncoupled to other frequencies.

In August 1996 I posted a message to biosonar or bioacoustics-1 which said (in part)

"Apart from the mammalian hearing issue, there are probably other concerns for animals sufficiently close to the source. Crudely modelling the human lungs as a spherical collection of air and soft tissue with between 5-95% air content and 6 litres capacity, I get resonance frequencies of around 80-l 80 Hz at 10m depth. These values rise to 140-320 Hz at 50m depth. "

The tissue/air mixture lowers the resonant frequency, compared to an all-air bubble. The rib cage rigidity prevents the lungs reducing in volume as much as would be due for a free bubble, also reducing resonant frequency at depth and perhaps raising it at atmospheric pressure. I just ignored the rib cage (OK for small displacements), included something for the lung tissue and modelled the lung as a homogeneous mixture of soft tissue and air, rather than an all-air bubble.

The crude estimates above make it quite clear that lung resonance in marine mammals might be an important mode for damage from LFA. Obviously these estimates deserve to be improved before such a mechanism can be discounted. Accurate estimates for real marine mammal air spaces will be difficult to obtain, and may best be evaluated numerically using a finite element code.

I believe that Dr Bill Marsh at Planning Systems Incorporated, San Diego knows people with complex lung models that cold be used to evaluate this potential risk more thoroughly. I am aware that there is debate on the meaningfulness of these models as they predict the resonant frequency decreases with depth, which is contrary to phenomenological expectations, but I believe that funding should be provided by the US Navy to improve these models and resolve such outstanding issues so that this risk can be **modelled** and quantified with confidence.

Sincerely,

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31 May 2001

Corollary comments on the proposed ruling to permit use of the US Navy's "Surveillance Towed Array Sensor System Low Frequency Active Sonar" (LFA).

Dear Ms. Wieting:

Thank you again for the opportunity to comment on NMFS' proposed rulemaking for the Navy's SURTASS LFA system. I have sent a main set of comments earlier today. These are in the way of a corollary. My qualifications include a Ph.D. in oceanography and glaciology with some 20 years' experience working in these fields and underwater acoustics, more recently including marine mammal acoustics.

With regard to potential hearing damage in marine mammals, following the best scientific information available (which is disagreeably sparse), it appears (from several independent lines of reasoning) that a Permanent threshold Shift (PTS) may be expected to occur in some marine mammal species at approximately 170 dB re 1 microPascal. If the requirement is to avoid permanent damage to marine mammals, this must be the absolute maximum level approved as a never-exceed value. This estimate is intended to be unbiased; i.e. it does not err on the side of safety, it is estimated so as to have equal probability of being too high as too low. For practical purposes, there is good reason to err on the side of safety (in a limited application of the precautionary principle) and so, if this level were to be adjusted, it would have to be downward, not upward.

The best available scientific information also indicates that Temporary threshold Shift (TTS) may be expected when some marine mammals are exposed to levels of approximately 160 dB re 1 microPascal for 60 seconds. This might reasonably be taken (in the absence of more sophisticated models, at present unjustified by the sparseness of scientific data and understanding) as the integrated exposure guideline, the intensity level integrated over time not to exceed 160 dB for 60 seconds.

In conclusion, it seems that potential noise polluters in the LFA band need to monitor exposure to animals at levels of 160 dB and above for continuous, or quasi-continuous (longer than the integration time of the mammalian ear), noise with an absolute never-exceed level of 170 dB in order to reasonably expect no physiological damage. Using a linear accumulation model, the total exposure at 160 dB should not to exceed 60 seconds. Total exposure at 166 dB not to exceed 30 seconds, and so on. Total accumulated exposure should be an integrated product of intensity and duration.

This is just to avoid TTS and PTS. If there is a more stringent need to prevent non-physiological damage, then the permitted levels would need to be lower.

For LFA, the above guidelines for avoiding physical damage require the Navy to be able to detect, classify and monitor marine mammals within a range of about 100 km from the LFA array, assuming they only want to make a single 60s transmission. If they want to make repeated transmissions, they would need to monitor a much larger area. The never-exceed limit implies that they would need to make sure no marine mammal ever got within 10 km of the LFA source array during a transmission. Neither of these requirements is remotely achievable at present.

Finally, there is a completely separate concern over lung volume resonance in marine mammals which requires more detailed study to model lung response over a range of volumes and diving depths.

Sincerely,

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